Development of an unmanned aerial vehicle stabilizing system with variable trust vectors

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Abstract. The unmanned aerial vehicle created on the base of a quadcopter with the ability to control the trust vector for each motor will have an advantage in comparison with the same vehicle without this option. This advantage reaches due to the possibility to create moving forces and reactions on the external excitations, without a pitch and roll angles of the whole body. With the help of control trust vector, unmanned aerial vehicles can move in space with a completely horizontal position. However, to control this system it is necessary to take into account a lot of parameters and addiction, so there are many ways to drive such a vehicle.

1. Introduction

Aviation, as a highly developed industry in terms of technology, cannot use all the modern ideas and technologies at once because of its planned future, and very high reliability requirements for the applied technologies. This gap is being filled by small, remotely controlled aircrafts, due to the fact that this segment does not yet have strict rules and requirements, despite its demand. The ability to solve similar tasks with large aircraft that do not concern the transportation of passengers, modern unmanned aerial vehicles are actively conquering markets for air monitoring, advertising, agricultural assistance, videotaping and another sphere. But standard aerodynamic schemes of UAV are strictly limited in flight and technical characteristics by available power setups. That is why everywhere new schemes and types of unmanned aerial vehicles (UAV) are developing [1], [2].

It is possible to expand the UAV's field of application by applying non-standard aerodynamic schemes and structures. For example, heli-planes [3] or variable airframe geometry. Using of new mechanisms and schemes is possible due to absence of strict requirements about reliability and safety for the UAV in comparison with full-size aircraft.

Our idea is to improve flight and technical characteristics of the UAV by controlling the thrust vector of each motor. This will slightly increase the range of the drone by reducing aerodynamic drag during the cruise flight, as well as maintain controllability in strong side winds. The control system, we are developing, should allow realizing these advantages. Application of the controlled trust vectors for the UAV is not evident, because of the complexity and weight of the mechanisms, and the lack of an unambiguous control algorithm [4], [5], [6].

2. Model tasks

During this project, we are creating and implementing a program to stabilize the UAV. As a basis we use the open project ARDUPILOT, in which we implement our model. This implementation method will allow us to assemble a full-fledged aircraft model with the least time and effort. With the help of such a model we will be able to prove the correctness of the approach, to compare its advantages and disadvantages with our existing analogues [7], [8].

When creating an experimental model, we accept several assumptions:

- We are not going to implement the position holding function, so all we have to do is to teach our program how to parry external influences and keep balance and horizontal.
- The model will be tested on a specially designed stand that implements 4 degrees of freedom: roll, pitch, and movements in the horizontal plane. This is because there is no need to add functions to the algorithm to independently select the total thrust of the motors and compensate movement for yaw.
- The experimental model allows to simplify mathematical model of what is happening due to the presence of coaxial propeller. Thus, there is no need to take into account the change in inertia moment of the UAV at rotor tilts, as gyroscopic moments of two motors and propellers will fully compensate each other.

Our algorithm should be the basis for a full-fledged autopilot and, therefore, we take into account only the main factors that may affect the aircraft's ability to detach from the ground. We have chosen a ready-made flight controller board as the platform. The main criterion when choosing a board was the number of controlled outputs to control all degrees of freedom in our system.

3. Model description

As a prototype, we chose a model of quadcopter with the frame resembling the letter H. Each motor is able to rotate in transverse and longitudinal plane relative to the normal direction of flight. The choice of this model was because the rotation of the joints will be easier to produce and assemble. The rotating principles are illustrated on figure1, and figure 2

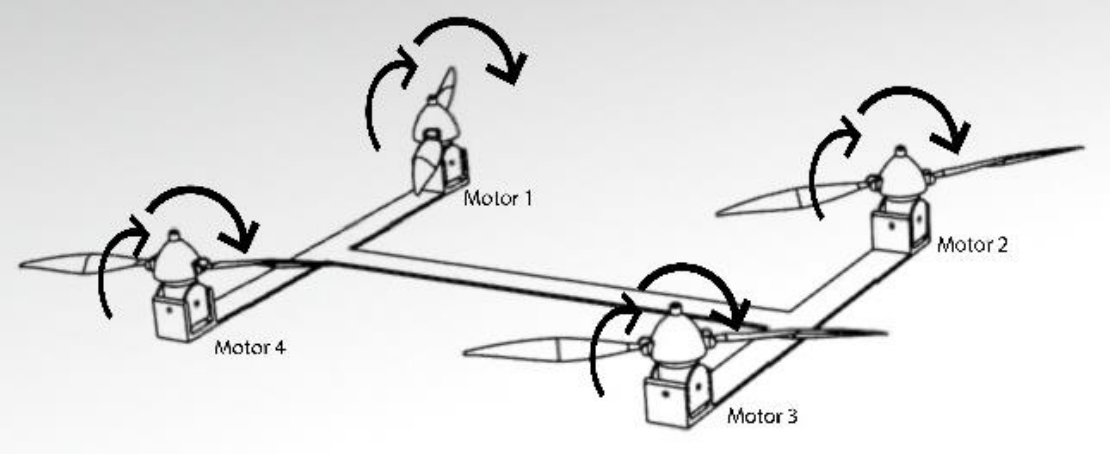

Figure 1. The general layout of the aircraft.

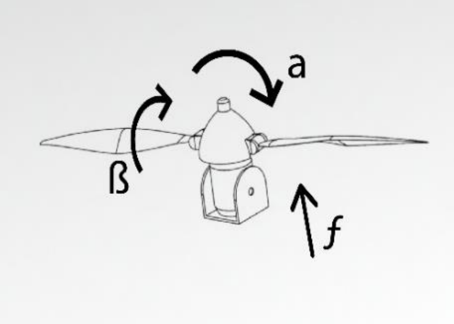

Figure 2. Degrees of motor freedom. In this illustration, we use the following designations: α- angle of each motor in transverse direction, is counted in clockwise direction by magnification when viewed from behind in the direction of UAV movement; β- angle of each motor in longitudinal direction, is counted in clockwise direction when viewed from the right; f - the traction force on each motor is determined by the motor speed. In this way, each motor has three controllable parameters.

As an idea for the algorithm, we see the function divided into two parallel processes. The first process aligns the device in the horizontal plane. The second process coordinates the UAV movement on the horizontal plane.

4. Mathematical model

First we will assume that drone is symmetrical body. Axis of symmetry passing throw the center of gravity.

Let us first consider the process of aligning the drone in the horizon. We will align our UAV by the difference in motor thrust, thus creating a stabilizing torque. We will also have to take into account the instantaneous position of the thrust vector to compensate for the torque created by this motor.

$$\sum M_{c.g.}(F_i)=0$$

The condition that the moments created by each motor are equal to the center of mass of the system. We must also take into account the instantaneous position of the traction vector to compensate for the moment created by this motor.

$$\sum f_i \cdot \cos(\alpha_i) \cdot \cos(\beta_i) \cdot l_i = 0$$

In this formula f_i - the force of traction created by the motor, l_i - the force arm of the motor, relative to the center of mass.

To maintain the horizontal position ($\theta = 0$ - pitch angle, $\varphi = 0$ - roll angle), we will create a stabilizing torque by adding and reducing the value of Δf to the motor draft force according to the PID rule of the regulator for the respective motors.

$$\begin{cases} M_{стаб} = \sum M_{стаб_i} = \sum \Delta f_i \cdot l_i \\ \Delta f_\theta(t) = P+I+D = K_p \cdot \theta(t) + K_i \int\limits_0^t \theta_\tau d\tau + K_d \dfrac{\mathrm{d}\theta}{\mathrm{d}t} \\ \Delta f_\varphi(t) = P+I+D = K_p \cdot \varphi(t) + K_i \int\limits_0^t \varphi_\tau d\tau + K_d \dfrac{\mathrm{d}\varphi}{\mathrm{d}t} \end{cases}$$

In this formula P-proportional summand, linearly depending on θ - pitch angle and K_P- coefficient of proportional summand. The I-integral summand depends on the sum of pitch changes for the whole period of reference. K_I-coefficient of the integral summand. The D-differential summand depends on the rate of pitch change - the angular velocity of the system, K_D-coefficient of the differential summand.

For realization of the second part of the algorithm, namely, counteraction to external disturbances in a horizontal plane and preservation of position by the quadcopter in space, we will change the direction of the thrust vector. This way we will create reaction forces in the horizontal plane f_x, f_y

$$f_x = \sum f_i \cdot \sin(\alpha_i) \cdot \sin(\varphi)$$

$$f_y = \sum f_i \cdot \sin(\beta_i) \cdot \sin(\theta)$$

In order to keep the position of the drone on the horizon, we will tilt the motors synchronously in the direction opposite to the direction of the external force by the angle Δα,Δβ. Here we also used PID regulator.

$$\begin{cases} \Delta\,\alpha(t) = P+I+D = K_p v_x(t) + K_i \int\limits_0^t v_{x_\tau} \mathrm{d}\tau + K_d \dfrac{\mathrm{d}v_x}{\mathrm{d}t} \\ \Delta\beta(t) = P+I+D = K_p v_y(t) + K_i \int\limits_0^t v_{y_\tau} \mathrm{d}\tau + K_d \dfrac{\mathrm{d}v_y}{\mathrm{d}t} \end{cases}$$

In order to check the feasibility of our idea, and to select the coefficients for the PID regulator, we created a model in Mat Lab. To find the coefficients for each quilted regulator we used the PID Tuner application in Mat Lab.

5. Simulation

Using the Simulink software package, we have created the following model figure 4.

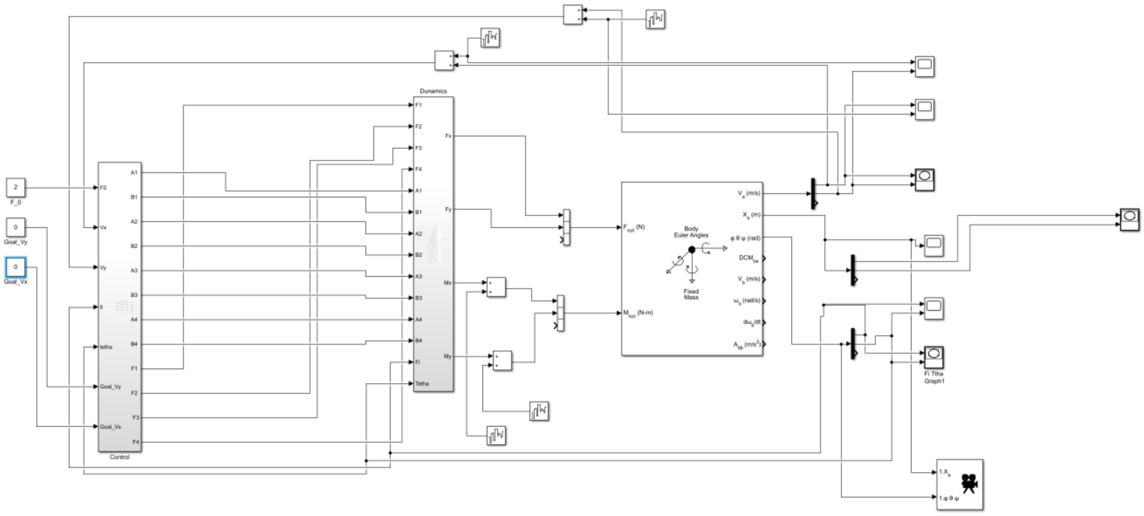

Figure 3. Designed Simulink model.

To simulate the behavior of the model we have created the following block (Figures 4 - 5.) This block implements all systems of equations described in the previous section.

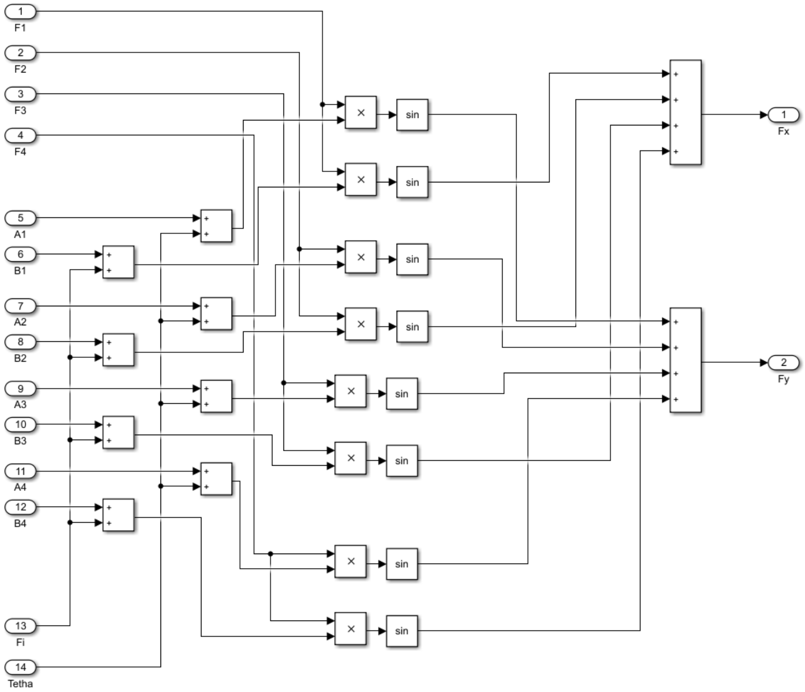

Figure 4. The forces acting on the model.

The working body is the following block shown in figure 6.

The described algorithm can be simulated in various ways. We have built a block in Simulink, which implements the equations described. Figure 7.

After building the model, we selected the coefficients for all four PID regulators. First the PID regulators were adjusted to stabilize the horizontal position, then to move.

6. Debugging

To evaluate the ability to resist external influences, we will consider how the system reacts to the short-term action of external torque. The result shown on figure 8.

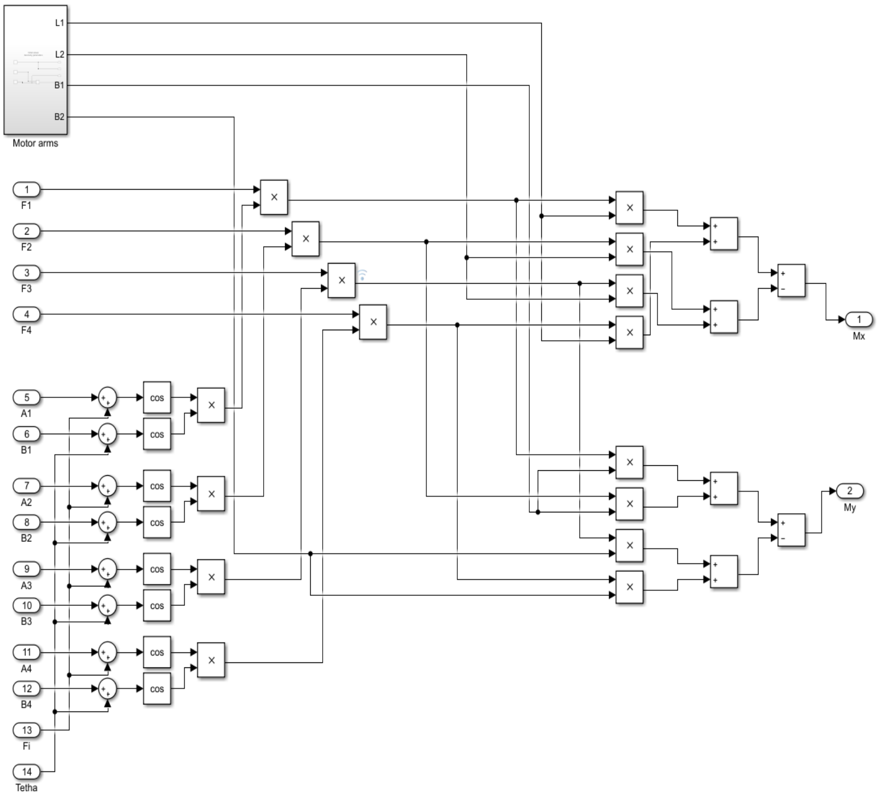

Figure 5. Moments acting on the model.

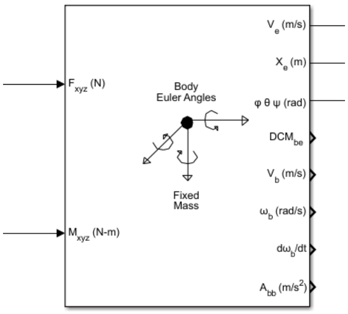

Figure 6. The body of an airplane
This unit is used to set parameters close to those of the model being designed. Required parameters can be obtained from the assembly model built in CAD program.

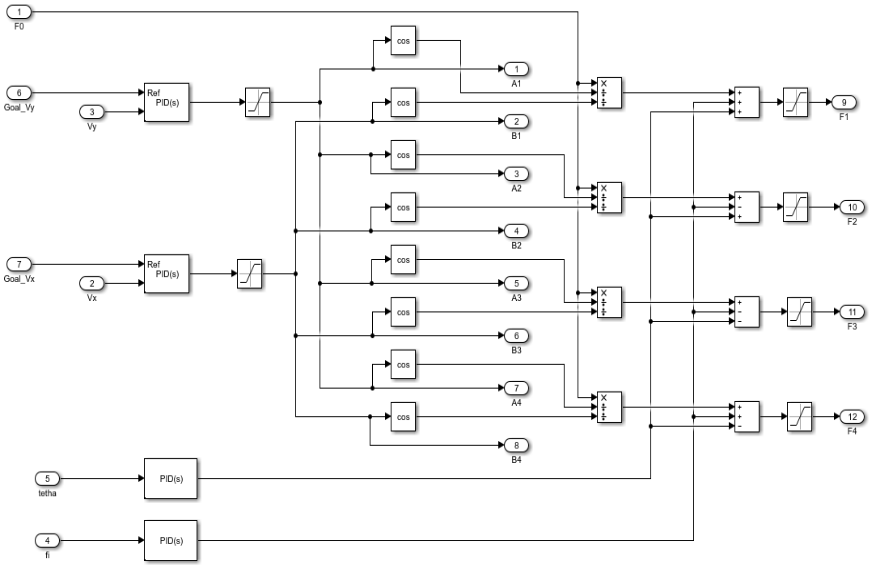

Figure 7. Stabilization system.

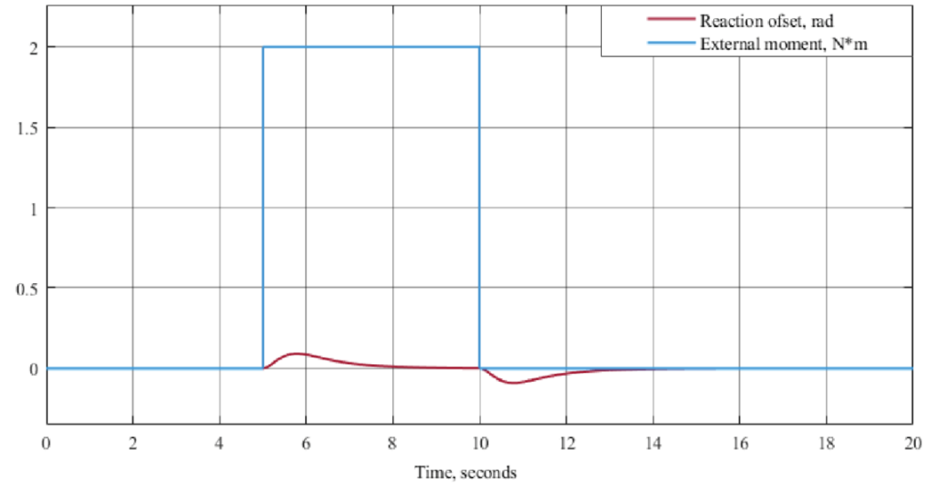

Figure 8. Reaction to the application of external torque.

It can be seen that to return to the original position of the model requires about 2seconds. This value can be considered sufficient, because we will stabilize a massive device weighing about 10 kg. In this example, we enclose an external torque equal to *2 N*m*. This value roughly corresponds to a flow of wind in vertical overhang with a speed of 7 m/s acting on half of the aircraft area.

Next, we need to consider how the system deals with external forces acting in the horizontal plane. For this purpose, random forces in size and direction will be applied to the horizontally placed aircraft. In this case, we will constantly ensure that the model does not change the angle of slope. Fig. 11 and Fig. 12 show examples for different frequencies of external oscillations changes. In Figure 9, the period of change in the external disturbances is 5 seconds. In Figure 10, the period is 10 seconds.

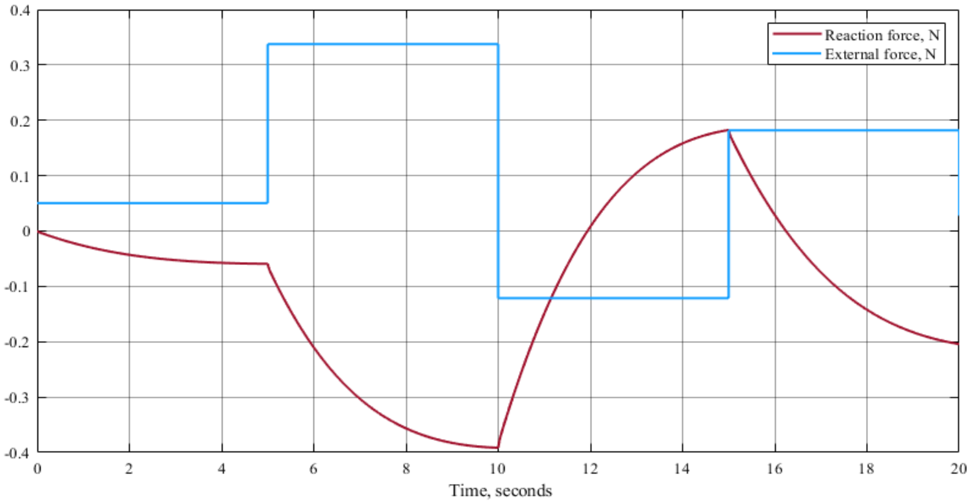

Figure 9. Reaction to external force. Period is 5 seconds.

7. Conclusion

Using such method, we can get the following advantage in comparison with the traditional control principle for no tilt-rotor quadcopter [4]. Let us say we have a choice how to create a force that counteracts the force of resistance from the side wind. We will also take the same propulsion and tilt angle. In the first case, reaction force will be reached by tilting the entire aircraft, and in the second case, it will be reaches by tilting the motor on the same angle. The force of displacement from the side wind will depend on the effective flow area, which will be larger when using the classical scheme.

The graph (Figure 11) shows the aerodynamic force dependence for each control model.

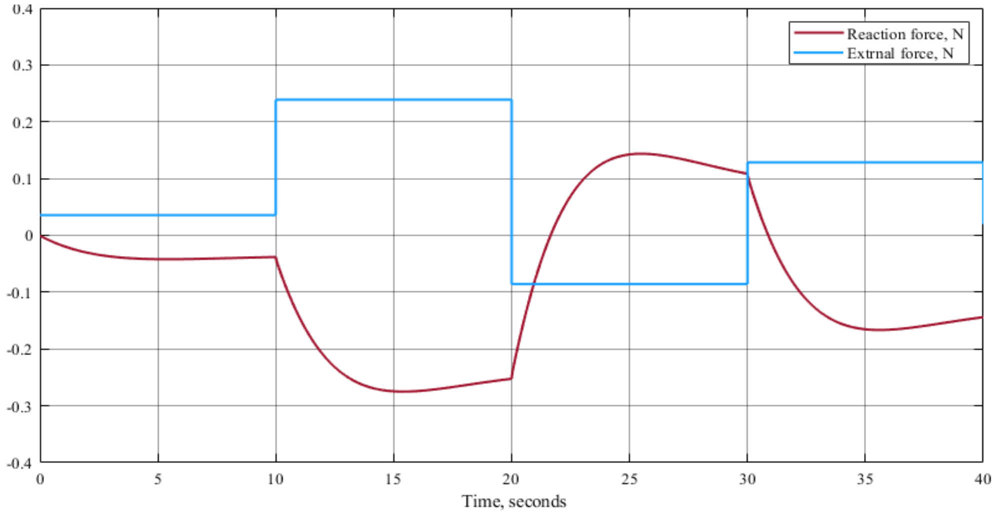

Figure 10. Reaction to external force. Period is 10 seconds.

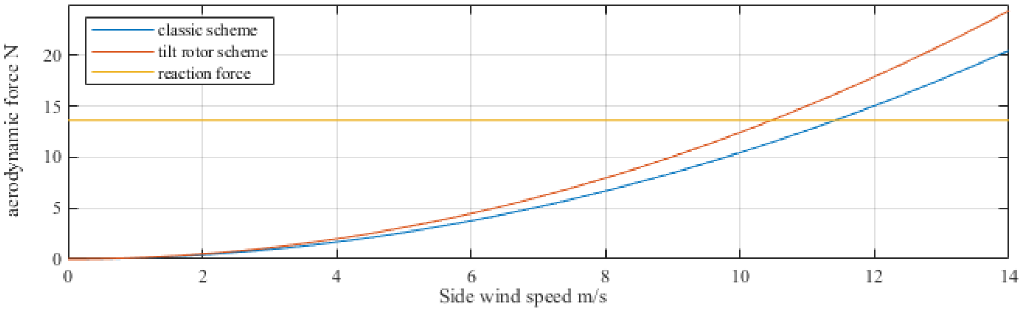

Figure 11. Aaerodynamic drag dependence for each control model.

In this way, the designed aircraft will be able to maintain control in the side wind of 11.5 m/s, while the classic scheme will lose control in the side wind of 10.2 m/s. These figures may vary greatly depending on the geometry and design of the aircraft. The results are approximate and applicable to the aircraft we are designing.

Thus, we have designed an algorithm that allows us to control an UAV with variable thrust vectors. This algorithm meets the requirements for the reliability of the advantages of such a drone scheme. We modeled the behavior of our model in the Mat lab program and tested the operation of our algorithm. Based on the described algorithm, we created a program that will be used for bench tests.

8. References

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